28. VIKING ORBITER 1975 ARTICULATION CONTROL ACTUATORS*

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ABSTRACT

A series of three (3) digital actuators will drive the scan platform, the high gain antenna, and the solar energy controller assembly on the VO'75 Mars orbiter spacecraft. The scan platform is a two (2) axis device for carrying and pointing the science instruments on the spacecraft. Motion for the two (2) axes (clock and cone) is provided by separate identical and interchangeable actuators. The high gain antenna also a two (2) axis (azimuth and elevation) device is kept pointed at the earth for the purpose of maintaining spacecraft control and communication. The antenna azimuth axis is driven by a scan actuator; the elevation axis is driven by an antenna actuator. The solar energy controller (SEC) is a louvre covered reflector assembly used for maintaining temperature control of the vector propulsion engine fuel tanks by regulating the sun radiation to the interior of the spacecraft. There are four (4) SEC assemblies on the spacecraft; each is driven by one actuator. All three (3) actuators have identical electrical schematics and identical electrical connectors. In the control system, one drive logic is used to drive each of the three (3) actuators. The control system is multiplexed in order that it can be time shared by all of the eight (8), two (2) scan, two (2) antenna, and four (4) SEC, articulation control subsystem actuators used on the spacecraft. Each actuator is a geared actuator using a stepper motor as its prime mover. Position feedback information (shaft angle) is provided by a potentiometer. The scan and antenna actuators have high precision low backlash gear trains. In order to do this, a beryllium metal gear housing is used. The beryllium housing closely matches the thermal coefficient of expansion of the gears. There are multidisk slip clutches in the scan and antenna actuators for the purpose of providing overload protection through the dynamic environment of launch and in ground handling during spacecraft test activity. Design experience is described and test results are discussed. Overall Viking Project management is the responsibility of NASA/Langley Research Center; the Jet Propulsion Laboratory is developing the orbiter.

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INTRODUCTION

The articulation control subsystem on the Viking Orbiter spacecraft will use eight actuators of three different sizes in order to perform its function. Each actuator will use a stepper motor as a prime mover and potentiometers for feedback control. The articulation control subsystem will have dual redundant channels and will be capable of multiplexed operation. The devices to be controlled are the platform containing the science instruments, the high gain antenna for earth communication and spacecraft control, and the solar energy controller used for temperature control of the vector engine fuel. The multiplex feature of the system will allow the control electronics to be time shared by all of the eight actuators. The dual redundant capability will allow any two axes to be articulated simultaneously and will allow any actuator to be driven by either one of its two command loops. Figure 1, a simplified subsystem diagram, will illustrate these features.

The scan (figure 2) and antenna (figure 3) actuators are very similar, both having identical gear reductions from motor to output shaft and two speed fine-coarse potentiometer shaft position readout capability. Each of these actuators will perform with constant low backlash throughout a large temperature range (-40°C to +85°C). The solar energy controller actuator (figure 4) does not have this precision requirement nor the two speed shaft position potentiometer readout capability; however, it must operate over the same temperature range. All of the actuators have identical electrical schematics and identical electrical connectors. A multidisk clutch (figure 5) is used for overload protection in the scan and the antenna actuator. The solar energy controller actuator does not have a clutch. This paper presents the design requirements, describes the actuator construction and gives the results of performance, life and environmental testing. Overall Viking Project management is the responsibility of NASA/Langley Research Center; the Jet Propulsion Laboratory is developing the orbiter.

DESCRIPTION

The actuators provide the controlled rotary motion for positioning and pointing the articulated devices on board the Viking Orbiter spacecraft. The articulated devices are the scan platform which mounts the science instruments, the high gain antenna which transmits data to earth from the science instruments and receives commands from earth for the control of the spacecraft or its science instruments, and the solar energy controller which regulates the solar energy in order to control the temperature of the vector propulsion engine fuel tanks. Each of the three actuators consists of five major parts. They are listed as follows:

1. A potentiometer for feedback control and telemetry data
2. A 90° per step permanent magnet stepper motor
3. A gear train
4. A gear train structure
5. An O-ring sealed housing

The housing is pressurized in order to protect the mechanism from corrosive gasses and to preserve the lubrication in the space vacuum environment. The gas used for pressurization is a mixture of 90% nitrogen and 10% helium by volume. The helium trace makes it possible to measure the actuator housing leak rate with a mass spectrometer leak detector since the leak is in the molecular flow regime. A resistance heater is mounted in the actuator on the gear structure to prevent damage due to low temperatures that will be encountered during the mission. A box mounting glass to metal hermetically sealed electrical connector is mounted on the actuator housing in order to provide for electrical inputs and outputs. The actuator's rotary motions are coupled to the articulated devices through either a bar linkage in the case of the SEC or an Oldham coupling as are the scan platform and high gain antenna. Mechanical stops are provided, by either the articulated devices or the actuator itself, that will limit the actuator shaft rotation in order to preserve position readout continuity from the potentiometer.

DESIGN REQUIREMENTS

The performance requirements may be generally described as motor voltage and power limits, gear train backlash, output torque, slewing speed, detenting torque, clutch slip torque, shaft angular range, and housing leak rate. The actuators must also be able to perform over a large temperature range and after being subjected to environmental testing. Specific values of Design Requirements are listed in the appendix.

GEAR STRUCTURE

In the scan and antenna actuators, the requirement for maintaining low backlash in the gear train over a large temperature range is satisfied by matching the thermal coefficient of expansion of the gears and gear train structure. In order to do this beryllium metal is used for the structure and precipitation hardening stainless steel is used for the shafts and gears. The differential expansion rate for these materials is 4×10^{-7} inch per inch per degree Fahrenheit. This differential rate is not sufficient to either bind the gears at the low temperature or cause undesirable backlash at the high temperature end. Beryllium metal was selected for the gear housing for the following reasons:

- Light weight
- Beryllium lends itself to precision fabrication very effectively
- The near match of the thermal coefficient of expansion of beryllium to that of the stainless steel gears which will keep the backlash within limits throughout the temperature range

The SEC actuator can function with a larger backlash allowance. This will allow the use of aluminum for its gear structure. Greater clearances in the gear meshes will accommodate the differential expansion. Its value is 6×10^{-6} inches per inch per inch per degree Fahrenheit.

GEARS

Spur gears were selected for the precision gear train because they are the least sophisticated to use. The simple straight spur gear is the best for precision application unless other requirements rule out its use. The spur gear mesh does not produce shaft axial thrust and is more efficient than helical, bevel, or worm gear meshes. Spur gears may be spring loaded in order to virtually eliminate backlash. This technique is used in the actuators in order to couple the potentiometers to the output shaft for angle readout information.

For maximum precision in the spur gear train 20° pressure angle gears have been selected. Minimum pitch size gears are used within the constraints required by load in order to maximize the contact ratio. Contact ratio may be described as the number of teeth simultaneously in contact in a pair of mating gears. The advantage of the high contact ratio is that it produces greater tooth-to-tooth error averaging which results in smoother tooth action and decreased tooth-to-tooth variable backlash and less position error. For this reason contact ratio with precision meshes should be maintained higher than those in commercial quality gears. A ratio of 1.4 or higher is desirable. The contact ratios used in these actuators are all above 1.6.

In selecting the best functional gear train for the actuators the gear ratio n is defined as the input angle divided by the output angle. The gear train performance parameters are described as follows:

1. The torque available at the output shaft, neglecting friction, is equal to the torque at the input multiplied by n.
2. The shaft speed of the output shaft is equal to the speed at the input shaft divided by n.
3. The angular acceleration at the output shaft which is a direct reduction of the speed variation is equal to the input acceleration divided by n.
4. The moment of inertia as reflected at the output shaft is a direct function of torque and an inverse function of acceleration; therefore, it is equal to the input moment of inertia multiplied by n^2.

GEAR STRESS

In order to determine the gear tooth stress, the Lewis gear formula modified to consider K_c the stress concentration factor, M_c the gear tooth contact ratio, P the gear pitch, T the torque applied, and N the number of teeth on the gear will be used:

$$S = \frac{2TP^2K_c}{NFYM_c}$$

Where F = face width, $Y = \pi y$, and y = tooth form factor

GEAR TRAIN BACKLASH

The gear train backlash was calculated by the use of an Root Sum Square (RSS) summation of gear and gearing worst case tolerances

$$\Delta\theta = \frac{360 \times 60 \tan \phi}{\pi R n} \left\{ x + \left[\bar{\Delta R}^2 + \bar{\Delta r}^2 + \bar{\Delta C}^2 + \left(\frac{\bar{\Delta D}}{2}\right)^2 + \left(\frac{\Delta d}{2}\right)^2 \right]^{\frac{1}{2}} \right\} \text{ minutes}$$

Where:

x = gear mesh center distance clearance
ΔR = tolerance on gear pitch radius
Δr = tolerance on pinion radius
R = gear pitch radius
$\frac{\Delta D}{2}$ = radial clearance in bearing - gear shaft
$\frac{\Delta d}{2}$ = radial clearance in bearing - pinion shaft
ΔC = tolerance on center distance
n = gear ratio from output shaft to mesh being evaluated
ϕ = gear pressure angle

BEARINGS

Journal bearings are used generously throughout the three actuators. The solar energy controller and the antenna actuators use all journal bearings except in their motors and potentiometers where ball bearings are installed. This is done in order to provide greater precision, maximum reliability, greater simplicity and reduction in cost. The friction loss in the actuator through the use of journal bearings is found to be not greater than 5% more than the friction losses in a similar actuator making use of ball bearings

whose friction is 100 times less than that of a journal bearing. The friction torque losses in the journal bearing equipped actuator were calculated by the following equation:

$$F = \frac{T}{R} f_c\ r\ \lambda, \text{ torque loss}$$

Where:

T = torque
R = gear radius
f_c = coefficient of friction
r = shaft radius
λ = gear efficiency

The friction losses may be computed for each shaft and summed.

ACTUATOR TORQUE

The pull out torque capability of a stepper motor is closely related to the inertia of the load being driven by the actuator and the pulse rate of the input voltage (figure 6). It is also indirectly related to the temperature of the motor windings. Since the dc resistance of the windings increases with rising temperature, constant voltage input to the motor will result in a reduction of current in the windings linearly proportional to the rise in temperature. It is an inherent characteristic of the permanent magnet stepper motor that through one step it is analogous to a dc torquer. Considering this fact, the torque loss will now be linear and directly proportional to the current reduction caused by the increased temperature of the motor windings.

The relationship between load inertia and step rate is illustrated by typical performance data shown in figure 6. In the case of the actuators the inertia portion of the driven load plus the gears is reflected back to the motor and is inversely proportional to the square of the gear ratio. Since the gears have typically small mass and inertia values, the inertia of gears beyond the second stage from the motor can be neglected. In the stepper motor actuator at constant temperature and driven at a constant stepping rate, torque and inertia appear as dependent variables whose limiting sum will inhibit the motor from stepping. The relationship between torque and inertia is typically linear.

SLIP CLUTCH

The multidisk slip clutch (figure 5) used in the scan actuator and in the antenna actuator was tested by using a lathe as a test device (figure 7). A thermocouple was placed on the clutch, the load cell was calibrated and its

output was recorded on a strip chart recorder. Three lubricants were tested in the clutch. They are listed: Versilube G300, Krytox 240AC, and Versilube F50 plus MoS_2. The Versilube F50-MoS_2 combination lubricant provided the best results and was specified for use in the actuator clutches. This lubricant was also used in other clutches in the Mariner '69 and Mariner '71 scan platform actuators.

The clutch is set at 40 inch-pound slip torque and slipped in the lathe at 10 rpm with direction of rotation reversed every five minutes at room temperature. This procedure was used to evaluate the lubrication. The Versilube F50 plus MoS_2 in the clutch allowed it to have: 1) lower temperature rise; 2) longer slip time before torque change; 3) operation over a larger temperature range with lower torque change. In this condition driven at 10 rpm the clutch showed no change in torque to 1,600 turns. After 3,000 turns the torque increase was 25% to 50 inch-pounds. The test was terminated at 4,000 turns. The clutch torque was then at 60 inch-pounds. The clutch was cleaned, re-lubricated, and readjusted to 35 inch-pounds and its temperature raised to 100°C. Over a two hour period the clutch torque was 38 inch-pounds. The temperature was then lowered to -45°C. The clutch torque at that temperature was 48 inch-pounds.

The multidisk slip clutch used in the actuators is designed to be a high efficiency slip device wi. . loads comparable to those experienced in journal bearings. The coefficient of friction in this clutch is of the order of 0.1. The clutch disks are made of through hardened, brittle hard 440C stainless steel hardened to Rockwell C 62 working against beryllium copper half hard disks.

There are two methods of calculating the clutch friction torque. One, a classical method, is the uniform pressure method where the integration of the clutch torque equation will yield an average radius where force applied puts uniform pressure over the face of the disk. The other method is the uniform wear method where the average of the internal diameter and outside diameter of the disk divided by two yields the effective radius. Test results indicate the uniform wear analysis method being closer to the results obtained.

SUMMARY

The articulation subsystem actuators were rigorously tested in severe environments. They were operated through temperature ranges from -73°C to +121°C. In each case the temperature rate of change was at maximum. The actuator under test at room temperature was put into a pre-chilled or preheated chamber. Satisfactory performance was obtained throughout this full temperature range and under the temperature shock conditions above. However, at temperatures below -78°C some leakage was experienced through the O-ring seal around the shaft. The actuators were subjected to severe vibration tests at the qualification levels, both random noise and sinusoidal vibration. In addition to vibration, they were subjected to 500 g shock test with a time

duration of 0.0007 second. The scan actuator was life tested by operating it from stop to stop through 2,000 cycles with 20,000 start-stop procedures randomly distributed through the 2,000 cycles.

CONCLUDING REMARKS

At the conclusion of the test program the actuators met the performance requirements listed earlier in this report. The use of beryllium in the gear structures for the scan and antenna actuators represents an ideal application of beryllium. These actuators have now been qualified and will be used on the Viking Orbiter Spacecraft for the purpose of controlling the articulated devices on board. Overall Viking Project management is the responsibility of NASA/Langley Research Center; the Jet Propulsion Laboratory is developing the orbiter.

APPENDIX

Design Requirements

The actuators are designed to meet the following performance requirements:

(1) Motor voltage 28 VDC $\pm$ 10%

(2) Motor power limited to 10 watts

(3) Performance over temperature range $-40^{\circ}C$ to $+85^{\circ}C$

(4) Gear train backlash

Scan < 6 arc minutes

Antenna < 10 arc minutes

SEC < 30 arc minutes

(5) Actuator pullout torque at $25^{\circ}C$ while being driven at 100 pulses per second step rate

Scan > 160 inch-pounds

Antenna > 45 inch-pounds

SEC > 70 ounce-inches

(6) Driving speed at 100 pulses per second step rate

Scan	1°	per second
Antenna	1°	per second
SEC	14°	per second

(7) Detenting torque with motor unexcited

Scan > 250 inch-pounds

Antenna > 75 inch-pounds

SEC > 2 inch-pounds

APPENDIX
(continued)

(8) Clutch slip torque

Scan 250 to 400 inch-pounds

Antenna 80 to 160 inch-pounds

SEC no clutch installed

(9) Shaft angular range

Scan 250°

Antenna 200°

SEC 90°

(10) Actuator leak rate all actuators

< 0.08 standard cc per hour mixture

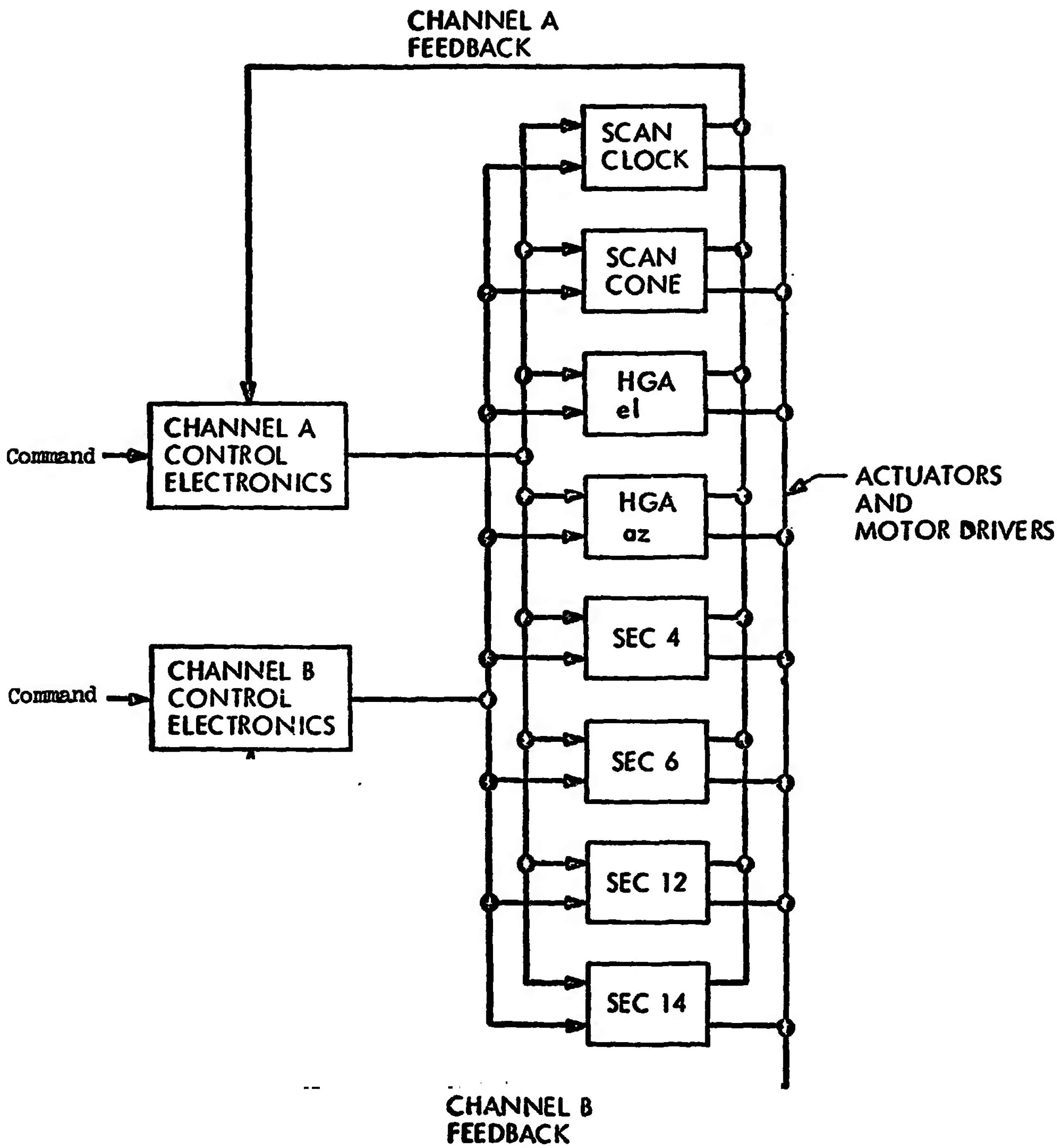


Figure 1.- Articulation control subsystem.

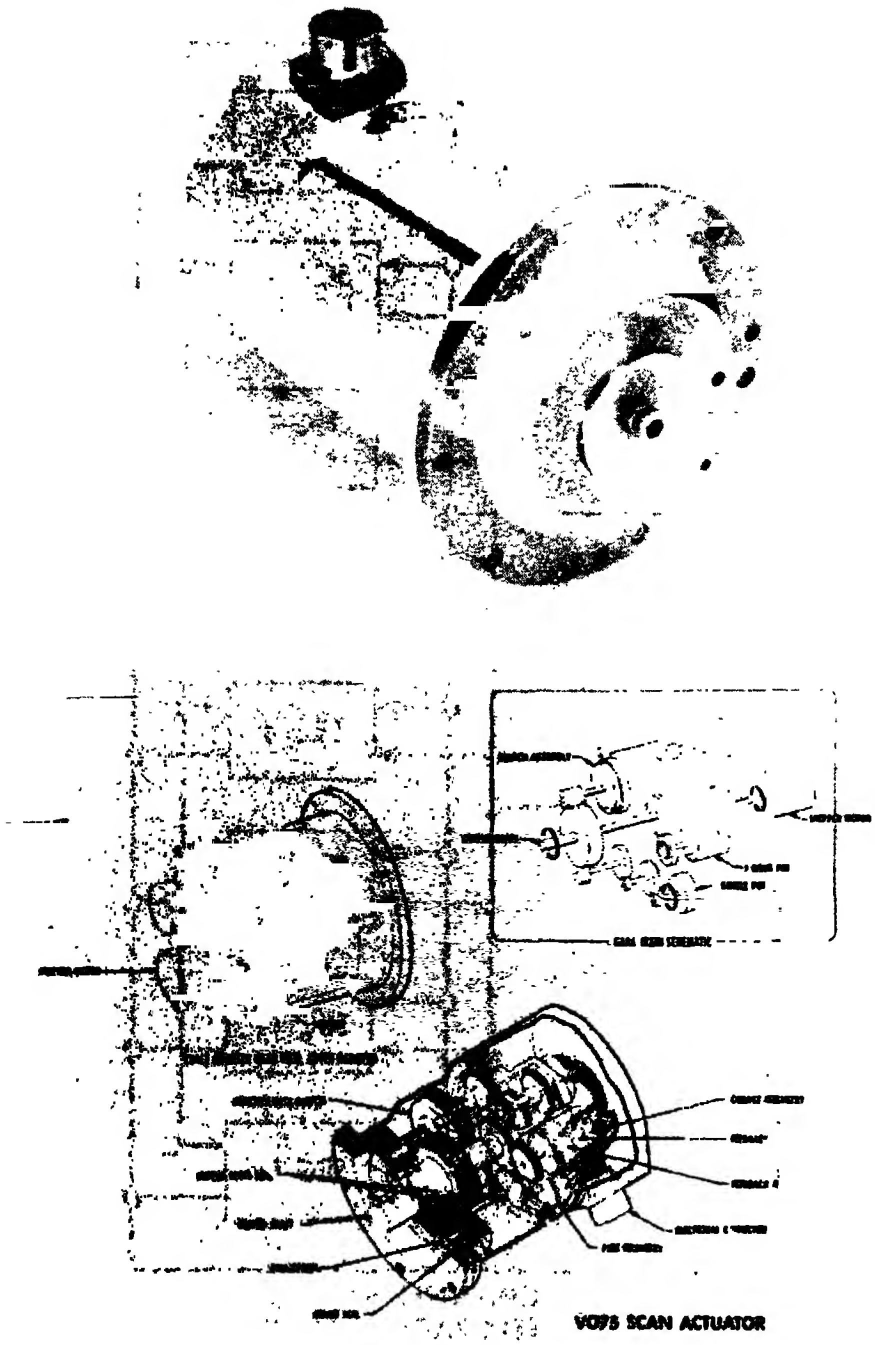
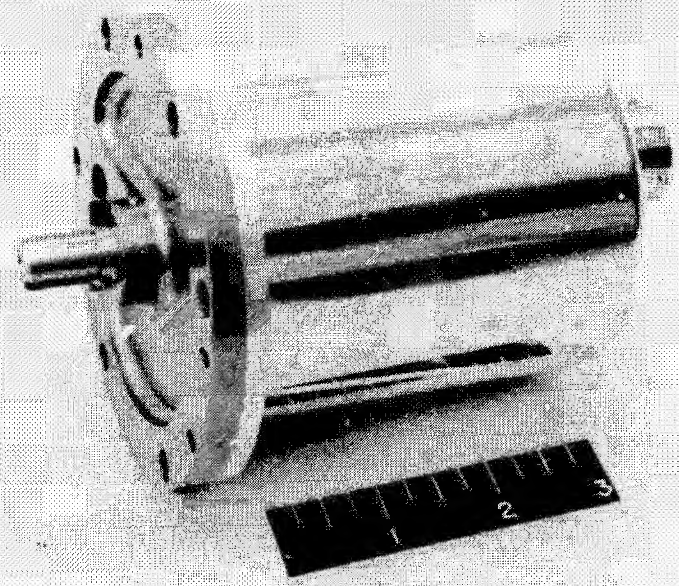


Figure 2.- VO'75 scan actuator.



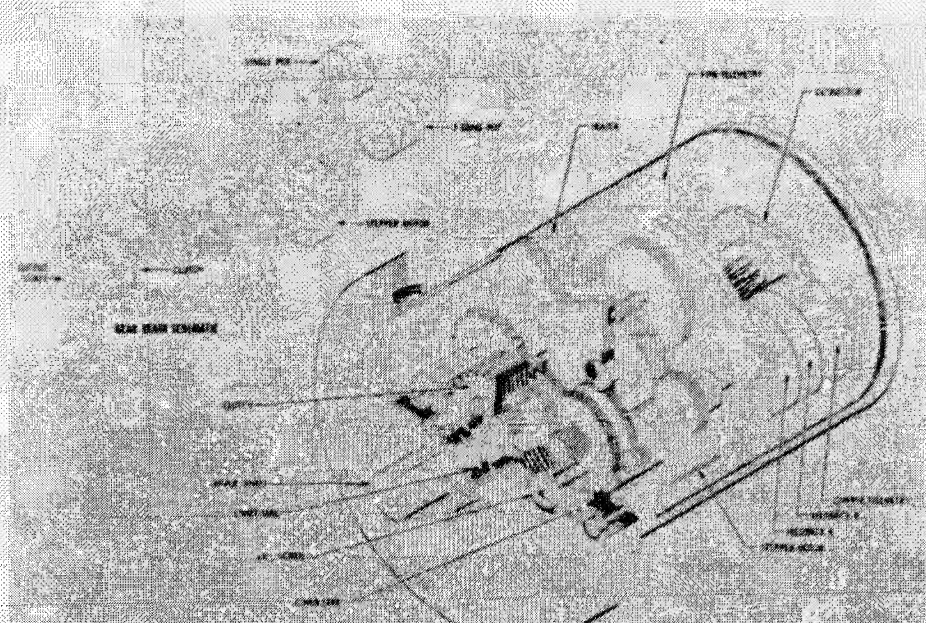


Figure 3.- VO'75 antenna actuator.

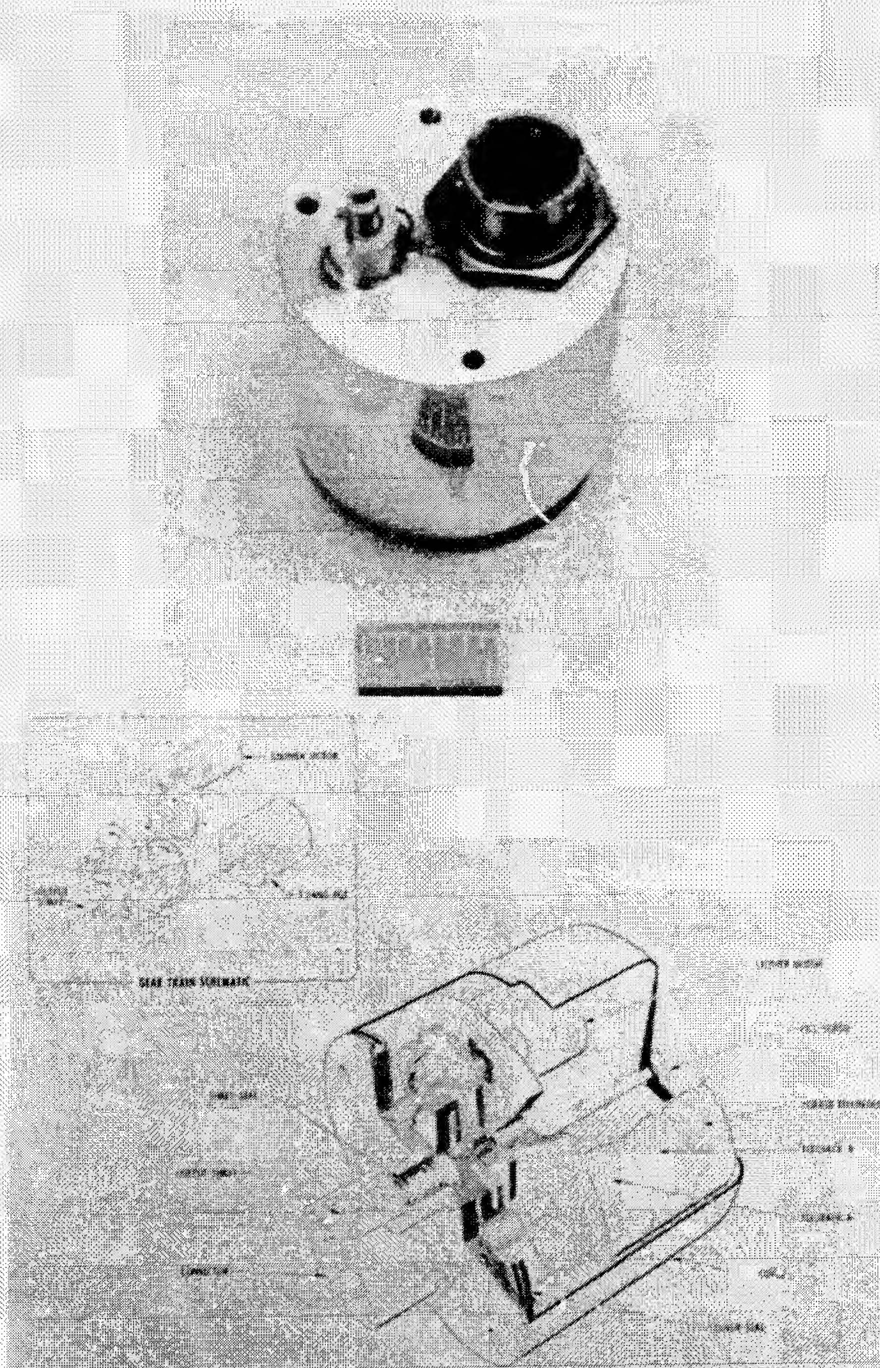


Figure 4.- VO'75 solar energy controller actuator.

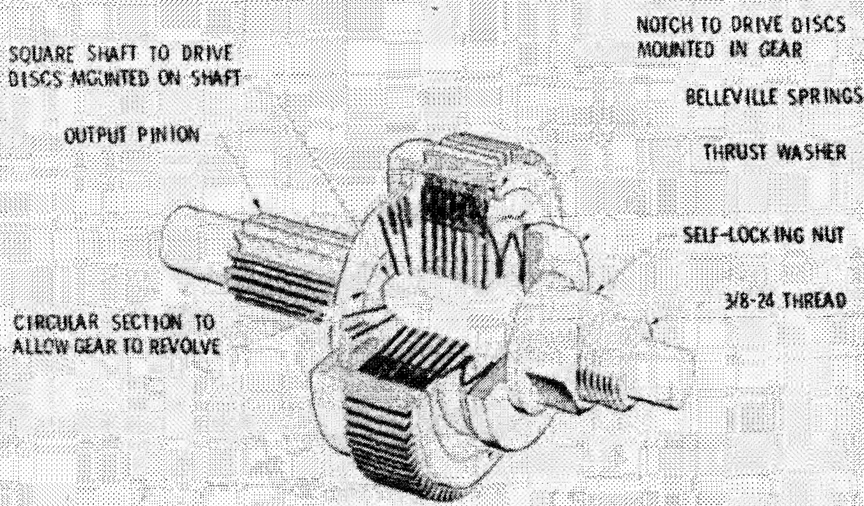


Figure 5.- Clutch assembly scan actuator.

Figure 6.- Stepper motor performance characteristics (scan actuator).

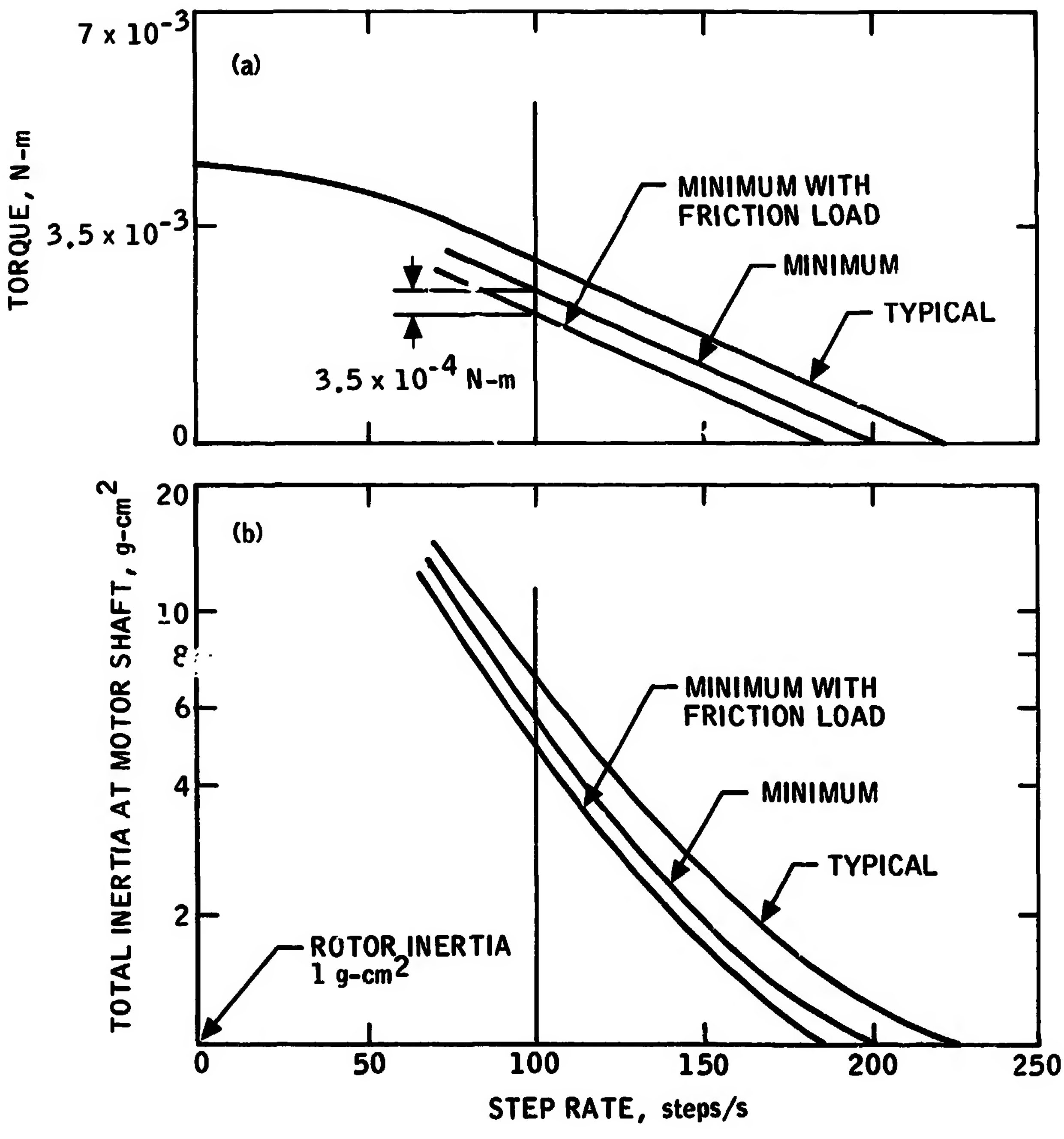

7 x 10-3
(a)
TORQUE, N-m
3.5 x 10-3
MINIMUM WITH FRICTION LOAD
MINIMUM
TYPICAL
3.5 x 10-4 N-m
0
20
(b)
TOTAL INERTIA AT MOTOR SHAFT, g-cm2
10
8
6
4
2
MINIMUM WITH FRICTION LOAD
MINIMUM
TYPICAL
ROTOR INERTIA 1 g-cm2
0
50
100
150
200
250
STEP RATE, steps/s

Figure 7.